APPENDIX C

Human Health Effects from Facility Accidents

APPENDIX C
HUMAN HEALTH EFFECTS FROM FACILITY ACCIDENTS

C.1 INTRODUCTION

Accident analyses were performed to estimate the impacts on workers and the public from reasonably foreseeable accidents for the Los Alamos National Laboratory (LANL) Technical Area 18 (TA-18) mission relocation alternatives. The analyses were performed in accordance with National Environmental Policy Act (NEPA) guidelines, including the process followed for the selection of accidents, definition of accident scenarios, and estimation of potential impacts. The sections that follow describe the methodology and assumptions, accident selection process, selected accident scenarios, and consequences and risks of the accidents evaluated.

C.2 OVERVIEW OF METHODOLOGY AND BASIC ASSUMPTIONS

The radiological impacts from accidental releases from the facilities used to perform TA-18 missions were calculated using the MACCS computer code, Version 1.12 (MACCS2). A detailed description of the MACCS model is provided in NUREG/CR-4691 (NRC1990). The enhancements incorporated in MACCS2 are described in the *MACCS2 Users Guide* (SNL 1997). This section presents the MACCS2 data specific to the accident analyses. Additional information on the MACCS2 code is provided in Section C.8.

As implemented, the MACCS2 model evaluates doses due to inhalation of airborne material, as well as exposure to the passing plume. This represents the major portion of the dose that an individual would receive as a result of a TA-18 mission facility accident. The longer-term effects of radioactive material deposited on the ground after a postulated accident, including the resuspension and subsequent inhalation of radioactive material and the ingestion of contaminated crops, were not modeled for this environmental impact statement (EIS). These pathways have been studied and found to contribute less significantly to the dosage than the inhalation of radioactive material in the passing plume; they are also controllable through interdiction. Instead, the deposition velocity of the radioactive material was set to 0, so that material that might otherwise be deposited on surfaces remained airborne and available for inhalation. This adds a conservatism to inhalation doses that can become considerable at large distances. Thus, the method used in this EIS is conservative compared with dose results that would be obtained if deposition and resuspension were taken into account.

The impacts were assessed for the offsite population surrounding each site, the maximally exposed offsite individual, and a noninvolved worker. The impacts on involved workers were addressed qualitatively because no adequate method exists for calculating meaningful consequences at or near the location where the accident could occur. Involved workers are also fully trained in emergency procedures, including potential accidents.

The offsite population is defined as the general public residing within 80 kilometers (50 miles) of each site. The population distribution for each proposed site is based on U.S. Department of Commerce state population projections (DOC 1999). State and county population estimates were examined to interpolate the data to the year 2001. These data were fitted to a polar coordinate grid with 16 angular sectors aligned with the 16 compass directions, with radial intervals that extend outward to 80 kilometers (50 miles). The offsite population within 80 kilometers (50 miles) was estimated to be 320,182 persons at TA-18 (the No Action Alternative and the TA-18 Upgrade Alternative); 283,571 persons at TA-55 (the LANL New

Facility Alternative); 745,287 persons at TA-V[1] (the Sandia National Laboratories/New Mexico [SNL/NM] Alternative); 18,074 persons at the Device Assembly Facility (DAF) (the Nevada Test Site [NTS] Alternative); 239,099 persons at Argonne National Laboratory-West (ANL-W) (the ANL-W Alternative); and 450,302 persons at TA-39 (the Solution High-Energy Burst Assembly [SHEBA] proposed relocation site). For this analysis, no credit was taken for emergency response evacuations or temporary relocation of the general public.

The maximally exposed offsite individual is defined as a hypothetical individual member of the public who would receive the maximum dose from an accident. This individual is usually assumed to be located at a site boundary. However, for some sites, there are public residences within the site boundary, such as the trailer park within the LANL site boundary. In these instances, the maximally exposed individual could be at these onsite locations.

The maximally exposed offsite individual location was determined for each site. The maximally exposed individual location can vary at a site based on the type of accident. Therefore, some sites may have more than one location for the maximally exposed offsite individual. For this analysis, the maximally exposed offsite individual is located at 1.1 kilometers (0.7 miles) to the northeast (TA-18); 1 kilometer (0.6 miles) to the north and 2.6 kilometers (1.6 miles) to the east-southeast (TA-55); 2.0 kilometers (1.2 miles) to the northeast and to the north (TA-V); 10.9 kilometers (6.8 miles) to the east-northeast (DAF); 5.2 kilometers (3.2 miles) and 6.7 kilometers (4.2 miles) to the south-southeast (ANL-W); and 0.8 kilometers (0.5 miles) to the southwest (TA-39).

A noninvolved worker is defined as an onsite worker who is not directly involved in the facility activity pertaining to the accident. The noninvolved worker is assumed to be exposed to the full release, without any protection, at various distances from the point of release from facilities depending on the alternative or action being assessed. For SHEBA, this distance would be 400 meters (1,310 feet); for the other TA-18 mission facilities, this distance would be 400 meters (1,310 feet) if the facilities remain at TA-18, and 100 meters (330 feet) if the missions are relocated to TA-55, SNL/NM, NTS, or ANL-W. Workers would respond to a site emergency alarm and evacuate to a designated shelter area, reducing their exposure potential. For purposes of the analyses, however, it was conservatively assumed that no evacuation would take place.

Doses to the offsite population, the maximally exposed offsite individual, and a noninvolved worker were calculated based on site-specific meteorological conditions. Site-specific meteorology is described by one year of hourly windspeed atmospheric stability and by rainfall recorded at each site. The MACCS2 calculations produce distributions based on the meteorological conditions. For these analyses, the results presented are based on mean meteorological conditions. The mean produces more realistic consequences than a 95th percentile condition, which is sometimes used in accident analyses. The 95th percentile condition represents low-probability meteorological conditions that are not exceeded more than 5 percent of the time.

As discussed in Appendix B, the probability coefficients for determining the likelihood of a latent cancer fatality for low doses or dose rates are 0.0004 and 0.0005 fatal cancers per rem, applied to individual workers and individuals in the general public, respectively. For high doses received at a high rate, respective probability coefficients of 0.0008 and 0.001 fatal cancers per rem were applied for individual workers and individuals in the general public. The higher-probability coefficients apply where individual doses are above 20 rad or dose rates are above 10 rad per hour.

The preceding discussion focuses on radiological accidents. Chemical accident scenarios were not evaluated, since inventories of hazardous chemicals to support TA-18 operations do not exceed the Threshold Planning Quantities as stipulated on the Extremely Hazardous Substances List provided in Section 3.02 of the

[1] *Technical areas at Sandia National Laboratories/New Mexico are designated using roman numerals.*

Emergency Planning and Community Right-to-Know Act (EPA 1998). No specific analyses of the results of terrorist or sabotage acts were evaluated in this EIS. The U.S. Department of Energy (DOE) is considering impacts from sabotage in a separate analysis. Once completed, this analysis will be incorporated as a classified appendix in the final EIS. Industrial accidents were evaluated and the results are presented in Section C.7.

C.3 ACCIDENT SCENARIO SELECTION PROCESS

In accordance DOE NEPA guidelines, an EIS should, to the extent applicable, contain a representative set of accidents that includes various types such as fire, explosion, mechanical impact, criticality, spill, human error, natural phenomena, and external events. DOE's Office of NEPA Oversight, in the *Recommendations for the Preparation of Environmental Assessments and Environmental Impact Statements*, the "Green Book" (DOE 1993), presents recommendations for determining which accident scenarios to analyze.

The accident scenario selection was based on evaluation of accidents reported in the *Basis for Interim Operations (TA-18 BIO)* (DOE 2001). The selection and evaluation of accidents in the *TA-18 BIO* was based on a process described in the *DOE Standard: Preparation Guide for U.S. Department of Energy New Reactor Nuclear Facility Safety Analysis Reports (New Reactor SAR Preparation Guide)* (DOE 1994a). The accident selection process for this EIS is described in Sections C.3.1 through C.3.3 for Steps 1 through 3, respectively.

C.3.1 Hazard Identification – Step 1

Hazard evaluation, or hazards analysis, is the process of identifying the material, system, process, and plant characteristics that can potentially endanger the health and safety of workers and the public and then analyzing the potential consequences to humans of accidents involving the identified hazards. The hazards analysis examines the complete spectrum of accidents that could expose members of the public, onsite workers, facility workers, and the environment to hazardous materials. The hazards present at TA-18 were identified by reviewing broad hazards lists, assessing the applicability to the facilities and activities at the site, and looking for possible unique hazards posed by the unique activities carried out at TA-18.

Hazards analysis teams were assembled by LANL to collect and review documentation pertinent to the activities, machines, and facilities at TA-18 (DOE 2001). They performed technical walk downs of each facility and observed, from the remote-control room, actual criticality experiments on the critical assembly machines. Technical discussions and interviews were held with TA-18 personnel covering the spectrum of activities carried out at the site. **Table C–1** indicates the range of activities investigated and assessed for inclusion in the hazards analysis.

Table C–1 TA-18 Activities Evaluated in the Hazards Analysis

Category	*Activity*
Detector development	Active interrogation
	Detector development and operation
Emergency response	Readiness activities
	Interagency training
	Criticality safety demonstration
	Low- and medium-dose radiography
Critical assembly machines	Storage of security Category I and II nuclear materials
	Manual handling of nuclear materials
	Licensed equipment operations (crane, hoist, forklift)
	Operation of special equipment (e.g., vacuum cleaner)

Category	***Activity***
Critical assembly machines (cont'd)	Detector development and operation
	Welding
	Radiation test object construction
	Use of CASA or miscellaneous buildings as temporary material access areas
	Temporary staging of vault materials into CASA workspace
	Transfer of FL-10 bottle contents
	Criticality safety demonstration
	Special nuclear materials handling demonstration
	Planned criticality
	Local mode of machine operation (Plan 2)
	Source handling
	Loading/unloading of core materials
	Machine setup and tear-down operations
	Uranium fuel solution handling (fueling, defueling, spill cleanup)
	Dosimeter retrieval
	Hand stacking, hand cranking of core materials
	Worker re-entry into CASA after operations
	Radiography (excludes linear accelerator)
	Radiography with linear accelerator
	Drum or counter assay
	Portal installation, development, and testing
	Package monitoring
	Transport of nuclear materials (truck, motorized cart, forklift)
	Uranium hexafluoride operations
	Propane bottle handling
Operation	Basic criticality safety class
	Advanced criticality safety class
	CASA maintenance
	Long-range alpha detector
Material protection, control, and accountability	Portal installation, development, and testing
	Package monitor development
	Accelerator operations
	Operation of portable linear accelerator
	Sealed neutron generators
Support activities	Work control
	Soldering
	Machinists
	General mechanical support
	Licensed equipment operations (cranes, hoist, forklifts, etc.)
	Welding, staff, and shop
	Gamma spectroscopy
	Source handling
	Health physics support
	Special nuclear materials moves
	Industrial hygiene support
	Handling gas cylinders
	Waste management

CASA = Critical Assembly Storage Area.
Source: DOE 2001.

Hazard tables were prepared for the TA-18 facilities and activities. A LANL team screened the hundreds of potential hazards in the hazard tables to develop a subset of approximately 400 major TA-18 radiological hazards for use in the preparation of the *TA-18 BIO* (DOE 2001).

C.3.2 Hazard Evaluation – Step 2

The LANL team preparing the *TA-18 BIO* subsequently screened the subset of approximately 400 major TA-18 radiological hazards developed in Step 1. Using a hazards analysis process based on guidance provided by the *New Reactor SAR Preparation Guide* (DOE 1994a), the 400 major hazards were reduced to 22 major accidents. The process ranks the risk of each hazard based on estimated frequency of occurrence and potential consequences to screen out low-risk hazards. The subset of 22 major accidents (i.e., 4 reactivity insertion accidents, 2 criticality accidents, 6 fire/explosion accidents, 6 natural-phenomena events, 1 external event, and 3 miscellaneous events) were identified for analysis in the *TA-18 BIO* (DOE 2001). Descriptions of critical assembly machines are provided in Appendix A.

C.3.3 Accidents Selected for This Evaluation – Step 3

The EIS team screened the subset of 22 major accidents analyzed in the *TA-18 BIO* (DOE 2001) to select a spectrum of accident scenarios for the No Action Alternative. The following accident categories were considered in the selection process:

- fire
- explosion
- uncontrolled reactivity insertion
- inadvertent criticality
- spill
- mechanical impact
- human error
- natural phenomena
- external events

Screening criteria used in the selection process included, but were not limited to: (1) consideration of the impacts on the public and workers of high-frequency/low-consequence accidents and low-frequency/high-consequence accidents; (2) selection of the highest-impact accident in each accident category to envelope the impacts of all potential accidents; and (3) consideration of only reasonably foreseeable accidents. The list of No Action Alternative accident scenarios was reviewed for applicability to the other reasonable alternatives evaluated in this EIS. In addition, hazards and accident analyses at the candidate sites were reviewed to determine the potential for accidents initiated by external events (e.g., aircraft crash, and explosions in collocated facilities) and natural phenomena (e.g., external flooding, earthquake, extreme winds, and missiles).

Accident scenarios that involved the spill of radioactive material or the release of radioactive material due to mechanical impacts of machines or storage containers were considered but not evaluated in this EIS. The explosion scenario envelopes the worker and public health and safety impacts of these potential scenarios, where machine and storage containers in the facility were breached by the force of the explosion. Accident scenarios initiated by human error are evaluated in this EIS. Human error can be the initiating event for the postulated inadvertent criticality and uncontrolled reactivity insertion accident scenarios.

The results of the Step-3 selection process are presented below for each of the accident categories.

Fire – The high-pressure spray fire on a Comet machine, with a plutonium core, was selected from the list of fire accidents evaluated in the *TA-18 BIO* because it has a potentially large impact. Unmitigated, the fire has the potential to damage the Comet machine plutonium core. This accident scenario is applicable to all alternatives, excluding activities involving SHEBA relocation.

Explosion – Hydrogen detonation in SHEBA was selected as the representative explosion accident scenario. This accident scenario was selected because the accident analyses postulated that the force of the explosion could damage not only the SHEBA core, but also storage containers in the facility and could release additional radioactive material. This scenario is applicable to the two alternatives that involve SHEBA, the No Action and TA-18 Upgrade Alternatives, and to SHEBA relocation.

Uncontrolled reactivity insertion – Since TA-18 operations involve tests with both solid and liquid cores, two uncontrolled reactivity insertion accident scenarios were selected for evaluation in this EIS. The uncontrolled reactivity insertion in Comet or Planet, with a plutonium core, was selected as a representative scenario for insertions into a solid core. This scenario is applicable to all alternatives, excluding activities involving SHEBA relocation.

The uncontrolled reactivity insertion in SHEBA, in the burst mode, was selected as a representative scenario for insertions into a liquid core. This scenario is applicable to the two alternatives that involve SHEBA (i.e., the No Action and TA-18 Upgrade Alternatives).

Inadvertent criticality – Since TA-18 operations involve the handling of both solid and liquid radioactive materials, two inadvertent criticality accident scenarios were selected for evaluation in this EIS. The first postulated scenario is a bare, fully reflected, or moderated metal criticality accident. This scenario is applicable to all alternatives but is not applicable to SHEBA relocation. The second scenario postulates an inadvertent solution criticality. Since the handling of radioactive solutions is primarily associated with SHEBA operations, the inadvertent solution criticality scenario is applicable to the two alternatives that involve SHEBA, the No Action and TA-18 Upgrade Alternatives, and to SHEBA relocation.

Natural phenomena (earthquake) – The earthquake-induced facility collapse, without fire, was selected as the representative natural phenomena-induced accident scenario. At TA-18, natural gas from broken pipelines that would otherwise cause a fire is released through the rubble and fails to reach a flammable mixture. This scenario is applicable to all alternatives and to SHEBA relocation. The failure (i.e., collapse) of existing facilities and proposed new facilities due to an earthquake is based on site-specific facility seismic design features and the return frequencies for earthquakes with forces that significantly exceed the design-basis earthquake for the facility. An earthquake with less force, causing less damage, could trap natural gas from broken pipelines, leading to a fire, but with a smaller source term and lower impacts.

External events (aircraft crash) – The locations of existing facilities and the proposed locations of new facilities were evaluated to determine the probability of an aircraft impacting the facility, penetrating the facility, and damaging equipment and/or storage containers, causing the release of radioactive material. In those cases where the probability was less than 1.0×10^{-7} per year (i.e., less than 1 chance in 10 million years), the postulated scenario is not considered credible and is not evaluated in the EIS. The only alternative considered vulnerable to the high-energy aircraft-crash accident scenario is the SNL/NM Alternative. The accident scenario is initiated by a large aircraft crashing into an underground facility. The frequency of this accident is estimated to be 6.3×10^{-6} per year. However, analysis showed that there would be no damage to the materials at risk and, therefore, no radiological release to the environment (SNL/NM 2001). Therefore, this accident was eliminated from further analysis.

The locations of the existing facilities and the proposed locations of new facilities were also evaluated to determine if an accident in an adjacent facility or in a collocated or shared facility supporting another mission could propagate or initiate an accident in a facility with a TA-18-related mission. No externally initiated reasonably foreseeable accidents were identified that could affect the relocated TA-18 mission facilities.

Table C–2 shows the correlation between accidents and alternatives.

Table C–2 Applicability of TA-18 Existing Facilities Accidents to Alternatives

Accident Scenario	*Alternatives*						*Relocation of Security Category III/IV and SHEBA*
	No Action	*TA-18 Upgrade*	*LANL New Facility*	*SNL/NM*	*NTS*	*ANL-W*	
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	Yes	Yes	Yes	Yes	Yes	Yes	No
Bare, fully reflected, or moderated metal criticality	Yes	Yes	Yes	Yes	Yes	Yes	No
High-pressure spray fire on a Comet machine with a plutonium core	Yes	Yes	Yes	Yes	Yes	Yes	No
Earthquake-induced facility failures without fire	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Uncontrolled reactivity insertion in SHEBA in burst mode	Yes	Yes	No	No	No	No	Yes
Hydrogen detonation in SHEBA	Yes	Yes	No	No	No	No	Yes
Inadvertent solution criticality	Yes	Yes	No	No	No	No	Yes

C.4 Accident Scenario Descriptions and Source Term

This section describes the accident scenarios and corresponding source term developed for the relocation of TA-18 operations. The spectrum of accidents described below was used to determine the consequences (public and worker doses) and associated risks. Additional assumptions were made when further information was required to clarify the accident condition, update some of the parameters, or facilitate the evaluation process; these are referenced in each accident description.

The source term is the amount of respirable radioactive material released to the air, in terms of curies or grams, assuming the occurrence of a postulated accident. The airborne source term is typically estimated by the following equation:

$$\text{Source term} = \text{material at risk} \times \text{damage ratio} \times \text{airborne release fraction} \times \text{respirable fraction} \times \text{leak path factor}$$

The material at risk is the amount of radionuclides (in curies of activity or grams for each radionuclide) available for release when acted upon by a given physical stress (i.e., an accident). The material at risk is specific to a given process in the facility of interest. It is not necessarily the total quantity of material present, but is that amount of material in the scenario of interest postulated to be available for release.

The damage ratio is the fraction of material exposed to the effects of the energy, force, or stress generated by the postulated event. For the accident scenarios discussed in this analysis, the value of the damage ratio varies from 0.1 to 1.0.

The airborne release fraction is the fraction of material that becomes airborne due to the accident. In this analysis, airborne release fractions were obtained from the *TA-18 BIO* (DOE 2001) or the *DOE Handbook* on airborne release fractions (DOE 1994b).

The respirable fraction is the fraction of the material with a 10-micrometer (micron) or less aerodynamic-equivalent diameter particle size that could be retained in the respiratory system following inhalation. The respirable fraction values are also taken from the *TA-18 BIO* (DOE 2001) or the *DOE Handbook* on airborne release fractions (DOE 1994b).

The leak path factor accounts for the action of removal mechanisms (e.g., containment systems, filtration, deposition) to reduce the amount of airborne radioactivity ultimately released to occupied spaces in the facility or the environment. A leak path factor of 1.0 (i.e., no reduction) is assigned in accident scenarios involving a major failure of confinement barriers. Leak path factors were obtained from the *TA-18 BIO* (DOE 2001) and site-specific evaluations.

Since the isotopic composition and shape of some of the nuclear materials are classified, the material inventory has been converted to equivalent amounts of plutonium-239. The conversion was on a constant-consequence basis, so that the consequences calculated in the accident analyses are equivalent to what they would be if actual material inventories were used. The following sections describe the selected accident scenarios and corresponding source terms for each alternative.

C.4.1 Uncontrolled Reactivity Insertion in Comet or Planet with a Plutonium Core

An uncontrolled reactivity insertion in Comet or Planet could occur if additional fissile material is inadvertently added to the plutonium core; the geometry of the core is changed so that it has a higher reactivity; neutron-absorbing material in the system is removed; or a substance is placed outside the core which improves the reflection of neutrons from the core back into the core. This reactivity can be added as an immediate step increase or as a gradually increasing reactivity.

The scenario assumes a step insertion of reactivity followed by a runaway power excursion accident in Comet or Planet with a plutonium core. The accident is initiated by an unplanned reactivity insertion in either a Comet or Planet machine caused by a large deviation from the experiment plan and other human errors. Core damage is possible depending on the amount of excess reactivity insertion. The extent of any core damage also depends on the insertion rate (fast or slow) and the operator's response in initiating reactor protection-system scram. Core damage can range from fuel surface oxidation to fuel melting. Fuel melting has a higher airborne release fraction than metal oxidation. For this analysis, an unmitigated case is evaluated (i.e., no credit is taken for reactor protection-system scram or opportunities for operator-initiated manual scram). For this accident scenario, a bounding reactivity[2] insertion of $0.80 is postulated. This level of reactivity insertion is in excess of the administrative control limit of $0.50 and, therefore, is extremely conservative. Appendix A, Section A.1, provides a detailed discussion of reactivity.

The estimated frequency of this event is 1.0×10^{-6} per year. The material at risk is approximately 27 kilograms (60 pounds) of plutonium-239 equivalent metal. The damage ratio is 1.0 (i.e., the accident causes the entire core to melt). The airborne release fraction is 0.01, and the respirable fraction is 1.0.

[2]*Reactivity is the fractional change in neutron multiplication factor from one neutron generation to the next. Reactivity in dollars is equal to the delayed neutron fraction corresponding to a multiplication factor of 1.002 for a plutonium-239 core.*

For the No Action Alternative, the leak path factor is assumed to be 1.0 because the buildings are not specifically designed to contain or filter releases. This results in a source term of approximately 270 grams (10 ounces) of plutonium-239 equivalent.

For the TA-18 Upgrade, LANL New Facility, SNL/NM, NTS, and ANL-W Alternatives, the leak path factor is assumed to be 0.001 due to the implementation of improved containment, including high-efficiency particulate air filtration systems. This results in a source term of approximately 0.27 grams (0.01 ounces) of plutonium-239 equivalent.

In addition to the plutonium release, there would also be a fission product release. The fission products, however, were not included in the source term because analysis showed that the fission product release consequence contribution would be a minute fraction of the plutonium release and would not change the presented results (DOE 2001).

C.4.2 Bare, Fully Reflected, or Moderated Metal Criticality

An inadvertent criticality of a solid metal fissile material assembly could occur if the number of neutrons leaking out of the system (and therefore not available for further fissions) is reduced by introducing or enhancing reflection of these neutrons back into the fissile material. The number of neutrons available to cause additional fissions directly affects a system's ability to become critical. Some neutrons leak out of a mass of fissile material and are not available for further fissions, but a reflector outside the fissile material returns many of these leaking neutrons back to the fissile atoms.

The accident is a solid criticality involving fissile material, reflectors, and moderators resulting from mechanical failures or human errors that lead to introduction or increase of reflection in the system. The accident may be caused by computational errors in criticality safety evaluations, mechanical failures, or human errors that lead to the introduction of moderators in the system, or by human errors in following procedures or established criticality safety limits. A single-pulse yield of 1.0×10^{17} fissions is assessed to be bounding for metal criticalities.

The estimated frequency of this event is 1.0×10^{-6} to 1.0×10^{-4} per year. For this analysis, the high end of the frequency range, 1.0×10^{-4} per year, was conservatively chosen. The damage ratio is 0.1. The respirable fraction is 1.0. The airborne release fractions are 0.5 (krypton, xenon); 0.2 (cesium, rubidium); 0.03 (barium, strontium); 0.05 (iodine); 0.07 (tellurium); 0.002 (ruthenium, rhodium); 0.03 (molybdenum, niobium, technetium); 0.0004 (cerium, zirconium); 0.0006 (lanthanum, praseodymium, neodymium, yttrium); and 0.004 (antimony). The damage ratio and the airborne release fractions were obtained from the *DOE Handbook* on airborne release fractions (DOE 1994b).

For the No Action Alternative, the leak path factor is assumed to be 1.0 because the buildings are not specifically designed to contain or filter releases. The radioisotopes were obtained from the *TA-18 BIO* (DOE 2001). The source term for the No Action alternative is presented in **Table C–3**.

For the TA-18 Upgrade, LANL New Facility, SNL/NM, NTS, and ANL-W Alternatives, the leak path factors are assumed to be 1.0 (noble gases), 0.01 (halogens), and 0.001 (particulates) due to the implementation of improved containment, including high-efficiency particulate air and charcoal filtration systems. The source terms for these alternatives are also presented in Table C–3.

Table C–3 Solid Criticality Source Terms

Isotope	*1×10^{17} Fissions Activity (curies)*	*No Action Alternative Release Activity (curies)*	*All Other Alternatives Release Activity (curies)*
Krypton-85	3.68×10^{-7}	1.48×10^{-8}	1.48×10^{-8}
Krypton-85m	0.0118	0.00059	0.00059
Krypton-87	0.566	0.0283	0.0283
Krypton-88	1.25	0.0625	0.0625
Rubidium-86	1.26×10^{-6}	2.52×10^{-8}	2.52×10^{-11}
Strontium-89	0.0000364	1.09×10^{-7}	1.09×10^{-10}
Strontium-90	1.54×10^{-6}	4.62×10^{-9}	4.62×10^{-12}
Strontium-91	0.199	0.000597	5.97×10^{-7}
Strontium-92	2.14	0.00642	6.42×10^{-6}
Yttrium-90	8.89×10^{-6}	5.33×10^{-10}	5.33×10^{-13}
Yttrium-91	0.0000198	1.19×10^{-9}	1.19×10^{-12}
Yttrium-92	0.0448	2.69×10^{-6}	2.69×10^{-9}
Yttrium-93	0.0952	5.71×10^{-6}	5.71×10^{-9}
Zirconium-95	0.000472	1.89×10^{-8}	1.89×10^{-11}
Zirconium-97	0.539	0.0000216	2.16×10^{-8}
Niobium-95	4.45×10^{-6}	1.34×10^{-8}	1.34×10^{-11}
Molybdenum-99	0.00150	4.50×10^{-6}	4.50×10^{-9}
Technetium-99m	5.24×10^{-6}	1.57×10^{-8}	1.57×10^{-11}
Ruthenium-103	5.26×10^{-6}	1.05×10^{-9}	1.05×10^{-12}
Ruthenium-105	0.0902	0.000018	1.80×10^{-8}
Ruthenium-106	0.00046	9.20×10^{-8}	9.20×10^{-11}
Rhodium-105	9.07×10^{-6}	1.81×10^{-9}	1.81×10^{-12}
Antimony-127	0.00242	9.68×10^{-7}	9.68×10^{-10}
Antimony-129	0.648	0.000259	2.59×10^{-7}
Tellurium-127	0.000216	1.51×10^{-6}	1.51×10^{-9}
Tellurium-127m	7.73×10^{-7}	5.41×10^{-9}	5.41×10^{-12}
Tellurium-129	0.132	0.000924	9.24×10^{-7}
Tellurium-129m	0.00019	1.33×10^{-6}	1.33×10^{-9}
Tellurium-131	5.53	0.0387	0.0000387
Tellurium-131m	0.0768	0.000538	5.38×10^{-7}
Tellurium-132	0.180	0.00126	1.26×10^{-6}
Iodine-131	0.000313	1.57×10^{-6}	1.57×10^{-8}
Iodine-132	0.309	0.00155	0.0000155
Iodine-133	0.233	0.00117	0.0000117
Iodine-134	13.0	0.065	0.00065
Iodine-135	3.43	0.0172	0.000172
Xenon-133	0.000385	0.0000193	0.0000193
Xenon-135	0.264	0.0132	0.0132
Cesium-136	0.00168	0.0000336	3.36×10^{-8}
Cesium-137	0.000015	3.00×10^{-7}	3.00×10^{-10}
Barium-139	1.36	0.00408	4.08×10^{-6}
Barium-140	0.0135	0.0000405	4.05×10^{-8}
Lanthanum-140	0.00307	1.84×10^{-7}	1.84×10^{-10}
Lanthanum-141	0.0502	3.01×10^{-6}	3.01×10^{-9}
Lanthanum-142	0.593	0.0000356	3.56×10^{-8}
Cerium-141	5.68×10^{-7}	2.27×10^{-11}	2.27×10^{-14}

Isotope	*1×10^{17} Fissions Activity (curies)*	*No Action Alternative Release Activity (curies)*	*All Other Alternatives Release Activity (curies)*
Cerium-143	0.002	8.00×10^{-8}	8.00×10^{-11}
Cerium-144	0.0000609	2.44×10^{-9}	2.44×10^{-12}
Praseodymium-143	1.45×10^{-7}	8.70×10^{-12}	8.70×10^{-15}
Neodymium-147	0.0000123	7.38×10^{-10}	7.38×10^{-13}

Sources: DOE 1994b, DOE 2001.

C.4.3 High-Pressure Spray Fire on the Comet Machine with a Plutonium Core

An operational accident could occur involving a fire on one of the experimental machines in the three TA-18 Critical Assembly Storage Areas (CASAs) while fueled with a plutonium core. For this analysis, the accident is assumed to occur on the Comet machine because it has the most material at risk. A high-pressure spray fire resulting from a leak on the motor side of the hydraulic system fuels the postulated fire. The hydraulic system is an integral part of the Comet machine. A puncture in the high-pressure portion of the system is presumed to produce a spray-like fire that directly impinges on the underside of the aluminum plate on which the special nuclear material is placed. The flame melts the aluminum plate and then the plutonium core.

The estimated frequency of this event is 1.0×10^{-6} per year. The material at risk is approximately 27 kilograms (60 pounds) of plutonium-239 equivalent metal. The damage ratio is 1.0. The airborne release fraction is 0.01 and the respirable fraction is 1.0.

For the No Action Alternative, the leak path factor is assumed to be 1.0 because the buildings are not specifically designed to contain or filter releases. This results in a source term of approximately 270 grams (10 ounces) of plutonium-239 equivalent. The fire adds heat to the release, creating buoyancy, which results in a different release pattern and, therefore, different consequences than the 270 grams (10 ounces) released in the uncontrolled reactivity insertion accident.

For the TA-18 Upgrade, LANL New Facility, SNL/NM, NTS, and ANL-W Alternatives, the leak path factor is assumed to be 0.1 due to the implementation of improved containment, including high-efficiency particulate air filtration systems. This results in a source term of approximately 27 grams (1 ounce) of plutonium-239 equivalent.

C.4.4 Earthquake-Induced Facility Failures without Fire

The accident scenario is initiated by an earthquake event. The event produces sufficient peak ground acceleration to initiate the common-cause collapse of all facilities and the release of respirable material without fire. The *TA-18 BIO* (DOE 2001) described other earthquake events, including an event with a fire. For a fire to occur, the earthquake event must be of sufficient magnitude to damage a natural gas line, while leaving structures substantially intact to retain the released gas. The concentration of the natural gas would build up in the structure and could potentially ignite. The earthquake event with a fire, as well as the other earthquake events, however, all lead to lesser releases than the bounding event in this analysis. Sufficient damage occurs in the bounding event that the leaking natural gas would be dispersed to the atmosphere through the rubble and, therefore, fail to accumulate to a flammable concentration.

The frequency of an earthquake event of this magnitude is estimated to be 0.0001 per year. The material at risk is approximately 360 kilograms (794 pounds) of plutonium-239 equivalent in various forms. The damage ratio is 1.0 for all material forms and facilities. The airborne release fractions for all facilities are 0.0 (metal); 0.00006 (ceramic); 0.002 (powder); 0.0002 (liquid); and 1.0 (gas). The respirable fraction for all facilities is 1.0 (metal, ceramic, gas); 0.3 (powder); and 0.8 (liquid).

For the No Action Alternative, the leak path factor is assumed to be 1.0 because the buildings are assumed to have failed with no potential to contain or filter releases. This results in a source term of approximately 17 grams (0.6 ounces) of plutonium-239 equivalent.

For the TA-18 Upgrade Alternative, the leak path factor is assumed to be 1.0 because the buildings are assumed to have failed with no potential to contain or filter releases. This results in a source term of approximately 17 grams (0.6 ounces) of plutonium-239 equivalent.

For the LANL New Facility, SNL/NM, NTS, and ANL-W Alternatives, the leak path factor is assumed to be 0.001 because the facilities would be located underground, creating an arduous leak path, especially for particulates. The material at risk is approximately 350 kilograms (770 pounds) of plutonium-239 equivalent due to the absence of SHEBA. This results in a source term of approximately 0.015 grams (0.0005 ounces) of plutonium-239 equivalent.

For SHEBA relocation to TA-39, the material at risk is approximately 10 kilograms (22 pounds) of plutonium-239 equivalent. Assuming the material at risk is in liquid form, the airborne release factor is 0.0002 and the respirable fraction is 0.8. The leak path factor for this accident is assumed to be 1.0. This results in a source term of 1.6 grams (0.056 ounces) of plutonium-239 equivalent.

C.4.5 Uncontrolled Reactivity Insertion in SHEBA in Burst Mode

Burst operations in SHEBA are conducted by gradually filling the critical assembly vessel (CAV) with fuel until a stable, delayed critical condition is achieved. The safety rod is then inserted to terminate neutron multiplication and additional fuel is added to the CAV, followed by rapid withdrawal of the safety rod to initiate the burst. An unanticipated or larger-than-planned prompt critical burst is postulated as a result of failed engineering and administrative controls. The unmitigated reactivity insertion accident is assumed to result in the overpressure rupture of the CAV. Vessel fragments are assumed to also impact material located in the SHEBA building.

The estimated frequency of this event is 1.0×10^{-6} per year. The material at risk is approximately 10 kilograms (22 pounds) of plutonium-239 equivalent metal in mostly metal form and very small amounts in ceramic and liquid forms. The damage ratio is 1.0 for all material forms. The airborne release fractions for the SHEBA core are 1.0 (metal, gas); 0.006 (ceramic, powder); and 0.00005 (liquid). The SHEBA building airborne release fractions are 0.0005 (metal); 0.005 (ceramic, powder); 0.00005 (liquid); and 1.0 (gas). The respirable fractions for the SHEBA core are 1.0 (metal, gas); 0.02 (ceramic, powder); and 0.8 (liquid). The SHEBA building respirable release fractions are 0.5 (metal); 0.4 (ceramic, powder); 0.8 (liquid); and 1.0 (gas). The leak path factor for this accident, regardless of location, is assumed to be 1.0 because the buildings are not designed to contain releases. This results in a source term of approximately 700 grams (25 ounces) of plutonium-239 equivalent.

C.4.6 Hydrogen Detonation in SHEBA

Hydrogen detonation could occur under certain conditions and involve nuclear materials placed in the SHEBA core and/or the SHEBA building. Normal high levels of ionizing radiation generated during SHEBA experiments can cause radiolytic decomposition of water and production of hydrogen. Under sufficiently high energy levels, hydrogen is released to the cover gas space. The unmitigated accident scenario assumes the cover gas system is not operating, resulting in hydrogen detonation or, under partial mitigation in which there is a partial failure of the cover gas system, hydrogen deflagration. For this analysis, the bounding hydrogen detonation scenario is evaluated.

The estimated frequency of this event is 0.0054 per year. The material at risk is approximately 0.9 kilograms (2 pounds) (ceramic); 0.009 kilograms (0.3 ounces) (liquid); 0.7 kilograms (1.5 pounds) (metal); and 0.00006 kilograms (0.002 ounces) (powder) of plutonium-239 equivalent. The damage ratio is 1.0 for all material forms. The airborne release fractions are 0.0005 (metal); 0.005 (ceramic, powder); and 0.00005 (liquid). The respirable release fractions are 0.5 (metal); 0.4 (ceramic, powder); and 0.8 (liquid). The leak path factor is assumed to be 1.0 because the buildings are not designed to contain releases. This results in a source term of approximately 2 grams (0.07 ounces) of plutonium-239 equivalent.

C.4.7 Inadvertent Solution Criticality in SHEBA

An inadvertent solution criticality could occur in a solution containing one or more fissile isotopes if one or more of the following occurs: (1) the fissile isotope concentration is increased; (2) the total solution mass increases; (3) the geometric configuration of the solution changes in a way that increases its reactivity; or (4) materials are placed outside the solution vessel that reflect neutrons back into the solution, thereby increasing its reactivity. It could occur in a vault or CASA used to support SHEBA operations. It would involve an enriched fuel solution such as uranyl fluoride or nitrate up to 93 percent enriched fuel. In the vault, the most likely initiating events are the reconfiguration of five or six FL-10 containers by maintenance personnel or a seismic event. In a CASA, the criticality could be initiated by mishandling, leading to a spill or reconfiguration such as excessive stacking/reflection. An inadvertent solution criticality could also occur in Building 168 in SHEBA caused by human errors such as miscalculation or inadequate transfers during a switchover to a new fissile solution. No other operations or activities within TA-18 are assumed to handle, stage, or store fissile solutions in sufficient quantities to pose a solution criticality concern. A total yield of 3×10^{18} fissions is assessed to be bounding for all expected postulated solution criticalities at TA-18.

The estimated frequency of this event is 1.0×10^{-6} per year. The material at risk is approximately 100 liters (26.4 gallons), with an assumed fuel composition of 0.855 percent uranium-234; 93.04 percent uranium-235; 0.269 percent uranium-236; and 5.836 percent uranium-238. The damage ratio is 1.0. The analysis assumes that 25 percent of the solution boils off and 75 percent remains in a bulk configuration. The airborne release fraction and respirable fraction are different for the boiled/ejected and nonejected fractions of the solution. The airborne respirable fractions are 1.0 (krypton, xenon); 0.001 (cesium, rubidium, rhodium, ruthenium, tellurium); 0.000625 (antimony, barium, cerium, lanthanum, molybdenum, neodymium, niobium, praseodymium, strontium, technetium, yttrium, zirconium); and 0.4375 (iodine). The unmitigated leak path factor is conservatively assumed to be 1.0 with no depletion or plate out during transport within the building. The resulting source term is presented in **Table C–4**.

Table C–4 Liquid Criticality Source Terms

Isotope	*3×10^{18} Fissions Activity (curies)*	*Release Activity (curies)*
Krypton-85	3.94×10^{-6}	3.94×10^{-6}
Krypton-85m	0.559	0.559
Krypton-87	44.8	44.8
Krypton-88	63.0	63.0
Rubidium-86	0.0000126	1.26×10^{-8}
Strontium-89	0.000327	7.88×10^{-9}
Strontium-90	0.0000194	2.04×10^{-7}
Strontium-91	2.91	1.21×10^{-8}
Strontium-92	81.3	0.00182
Yttrium-90	0.000551	0.0508
Yttrium-91	0.0000315	3.44×10^{-7}
Yttrium-92	0.352	1.97×10^{-8}
Yttrium-93	1.67	0.00022

Isotope	3×10^{18} Fissions Activity (curies)	Release Activity (curies)
Zirconium-95	0.00313	0.00104
Zirconium-97	18.6	1.96×10^{-6}
Niobium-95	3.41×10^{-6}	0.0116
Molybdenum-99	0.0374	2.13×10^{-9}
Technetium-99m	9.38×10^{-6}	0.0000234
Ruthenium-103	0.0000313	3.13×10^{-8}
Ruthenium-105	0.0969	0.0000969
Ruthenium-106	0.0000294	2.94×10^{-8}
Rhodium-105	4.93×10^{-6}	4.93×10^{-9}
Antimony-127	0.00891	5.57×10^{-6}
Antimony-129	3.03	0.00189
Tellurium-127	0.000345	3.45×10^{-7}
Tellurium-127m	7.73×10^{-6}	7.73×10^{-9}
Tellurium-129	1.67	0.00167
Tellurium-129m	0.00221	2.21×10^{-6}
Tellurium-131	42.1	0.0421
Tellurium-131m	1.01	0.00101
Tellurium-132	3.14	0.00314
Iodine-131	0.0033	0.00133
Iodine-132	1.17	0.512
Iodine-133	1.31	0.573
Iodine-134	78.0	34.1
Iodine-135	75.1	32.9
Xenon-133	0.000822	0.000822
Xenon-135	1.63	1.63
Cesium-136	0.00268	2.68×10^{-6}
Cesium-137	0.0000679	6.79×10^{-8}
Barium-139	7.93	0.00496
Barium-140	0.224	0.00014
Lanthanum-140	0.0224	0.000014
Lanthanum-141	0.819	0.000512
Lanthanum-142	10.6	0.00663
Cerium-141	4.80×10^{-6}	3.0×10^{-9}
Cerium-143	0.155	0.0000969
Cerium-144	0.00171	1.07×10^{-6}
Praseodymium-143	1.38×10^{-6}	8.63×10^{-10}
Neodymium-147	0.0002	1.25×10^{-7}

Source: DOE 2001.

C.5 Accident Analyses Consequences and Risk Results

Once the source term for each accident scenario is determined, the radiological consequences are calculated. The calculations vary depending on how the release is dispersed, what material is involved, and which receptor is being considered. Risks are calculated based on the accident's frequency and its consequences. The risks are stated in terms of additional cancer fatalities resulting from a release.

For example, if the dose to the maximally exposed individual is 10 rem, the probability of a latent cancer fatality is $10 \times 0.0005 = 0.005$, where 0.0005 is the latent cancer fatality probability factor. If the maximally exposed individual receives a dose in excess of 20 rem, the latent cancer probability factor is doubled to 0.001. Thus, if the maximally exposed individual receives a dose of 30 rem, the latent cancer probability factor is 30 × 0.001 = 0.03.

For a noninvolved worker, the latent cancer fatality probability factor is 0.0004 rather than the 0.0005 factor used for the public. If a noninvolved worker receives a dose of 10 rem, the probability of a latent cancer fatality is 10 × 0.0004 = 0.004. As with the maximally exposed individual, if the dose exceeds 20 rem, the latent cancer probability factor doubles to 0.008.

For the population, the same latent cancer fatality probability factors are used to determine the estimated number of latent cancer fatalities. The MACCS2 computer code calculates the dose to each individual in the exposed population and then applies the appropriate latent cancer probability factor (i.e., 0.0005 for doses less than 20 rem or 0.001 for doses greater than or equal to 20 rem). Therefore, for some releases, the estimated number of latent cancer fatalities will not be a straight multiplication from the population dose. For example, at TA-18, the uncontrolled reactivity insertion in SHEBA in a burst-mode accident results in a population dose of 6,580 person-rem with 3.93 estimated latent cancer fatalities. The estimated number of latent cancer fatalities is between the 0.0005 and 0.001 probability factors. The 0.0005 factor would yield 3.29 cancer fatalities and the 0.001 would yield 6.58 cancer fatalities. This indicates that some members of the population received doses in excess of 20 rem. Allowing the computer code to calculate the number of latent cancer fatalities results in a more realistic number of potential latent cancer fatalities than using a straight multiplication factor.

The following tables (**C–5** through **C–18**) provide the results, which are presented in two tables for each alternative. The first of these tables presents the consequences (doses and latent cancer probability), assuming the accident occurs. The second provides the annual cancer risks, taking into account the accident frequency.

Table C–5 Accident Frequency and Consequences under the No Action Alternative

		Maximally Exposed Offsite Individual		*Offsite Population* [a]		*Noninvolved Worker*	
Accident	***Frequency (per year)***	***Dose (rem)***	***Latent Cancer Fatalities*** [b]	***Dose (person-rem)***	***Latent Cancer Fatalities*** [c]	***Dose (rem)***	***Latent Cancer Fatalities*** [b]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	1.0×10^{-6}	8.70	0.00435	2,580	1.30	133	0.106
Bare, fully reflected or moderated metal criticality	0.0001	2.49×10^{-7}	1.25×10^{-10}	0.0000669	3.34×10^{-8}	2.58×10^{-6}	1.03×10^{-9}
Uncontrolled reactivity insertion in SHEBA in burst mode	1.0×10^{-6}	22.2	0.0222	6,580	3.93	339	0.271
High-pressure spray fire on a Comet machine with a plutonium core	1.0×10^{-6}	2.09	0.00105	2,180	1.09	6.28	0.00251
Hydrogen detonation in SHEBA	0.0054	0.0625	0.0000313	18.8	0.00942	0.909	0.000364
Earthquake-induced facility failures without fire	0.0001	0.413	0.000207	158	0.0792	5.96	0.00238
Inadvertent solution criticality in SHEBA	1.0×10^{-6}	0.000185	9.25×10^{-8}	0.058	0.0000288	0.00179	7.16×10^{-7}

[a] Based on a population of 320,182 persons residing within 80 kilometers (50 miles) of the site.
[b] Increased likelihood of a latent cancer fatality.
[c] Increased number of latent cancer fatalities.

Table C–6 Annual Cancer Risks Due to Accidents under the No Action Alternative

Accident	*Maximally Exposed Offsite Individual* [a]	*Offsite Population* [b, c]	*Noninvolved Worker* [a]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	4.35×10^{-9}	1.30×10^{-6}	1.06×10^{-7}
Bare, fully reflected or moderated metal criticality	1.25×10^{-14}	3.34×10^{-12}	1.03×10^{-13}
Uncontrolled reactivity insertion in SHEBA in burst mode	2.22×10^{-8}	3.93×10^{-6}	2.71×10^{-7}
High-pressure spray fire on a Comet machine with a plutonium core	1.05×10^{-9}	1.09×10^{-6}	2.51×10^{-9}
Hydrogen detonation in SHEBA	1.69×10^{-7}	5.09×10^{-5}	1.97×10^{-6}
Earthquake-induced facility failures without fire	2.07×10^{-8}	7.92×10^{-6}	2.38×10^{-7}
Inadvertent solution criticality in SHEBA	9.25×10^{-14}	2.88×10^{-11}	7.16×10^{-13}

[a] Increased risk of a latent cancer fatality.
[b] Risk of increased number of latent cancer fatalities.
[c] Based on a population of 320,182 persons residing within 80 kilometers (50 miles) of the site.

Table C–7 Accident Frequency and Consequences under the TA-18 Upgrade Alternative

Accident	*Frequency (per year)*	*Maximally Exposed Offsite Individual*		*Offsite Population* [a]		*Noninvolved Worker*	
		Dose (rem)	*Latent Cancer Fatalities* [b]	*Dose (person-rem)*	*Latent Cancer Fatalities* [c]	*Dose (rem)*	*Latent Cancer Fatalities* [b]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	1.0×10^{-6}	0.0087	4.35×10^{-6}	2.58	0.00129	0.133	0.0000532
Bare, fully reflected or moderated metal criticality	0.0001	2.49×10^{-10}	1.25×10^{-13}	6.69×10^{-8}	3.34×10^{-11}	2.58×10^{-9}	1.03×10^{-12}
Uncontrolled reactivity insertion in SHEBA in burst mode	1.0×10^{-6}	22.2	0.0222	6,580	3.93	339	0.271
High-pressure spray fire on a Comet machine with a plutonium core	1.0×10^{-6}	0.209	0.000105	218	0.109	0.628	0.000251
Hydrogen detonation in SHEBA	0.0054	0.0625	0.0000313	18.8	0.00942	0.909	0.000364
Earthquake-induced facility failures without fire	0.0001	0.413	0.000207	158	0.0792	5.96	0.00238
Inadvertent solution criticality in SHEBA	1.0×10^{-6}	0.000185	9.25×10^{-8}	0.0575	0.0000288	0.00179	7.16×10^{-7}

[a] Based on a population of 320,182 persons residing within 80 kilometers (50 miles) of the site.
[b] Increased likelihood of a latent cancer fatality.
[c] Increased number of latent cancer fatalities.

Table C–8 Annual Cancer Risks Due to Accidents under the TA-18 Upgrade Alternative

Accident	Maximally Exposed Offsite Individual [a]	Offsite Population [b, c]	Noninvolved Worker [a]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	4.35×10^{-12}	1.29×10^{-9}	5.32×10^{-11}
Bare, fully reflected or moderated metal criticality	1.25×10^{-17}	3.34×10^{-15}	1.03×10^{-16}
Uncontrolled reactivity insertion in SHEBA in burst mode	2.22×10^{-8}	3.93×10^{-6}	2.71×10^{-7}
High-pressure spray fire on a Comet machine with a plutonium core	1.05×10^{-10}	1.09×10^{-7}	2.51×10^{-10}
Hydrogen detonation in SHEBA	1.69×10^{-7}	5.09×10^{-5}	1.97×10^{-6}
Earthquake-induced facility failures without fire	2.07×10^{-8}	7.92×10^{-6}	2.38×10^{-7}
Inadvertent solution criticality in SHEBA	9.25×10^{-14}	2.88×10^{-11}	7.16×10^{-13}

[a] Increased risk of a latent cancer fatality.
[b] Risk of increased number of latent cancer fatalities.
[c] Based on a population of 320,182 persons residing within 80 kilometers (50 miles) of the site.

Table C–9 Accident Frequency and Consequences under the LANL New Facility Alternative

Accident	Frequency (per year)	Maximally Exposed Offsite Individual		Offsite Population [a]		Noninvolved Worker	
		Dose (rem)	Latent Cancer Fatalities [b]	Dose (person-rem)	Latent Cancer Fatalities [c]	Dose (rem)	Latent Cancer Fatalities [b]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	1.0×10^{-6}	0.00334	1.67×10^{-6}	2.89	0.00144	1.53	0.000612
Bare, fully reflected or moderated metal criticality	0.0001	1.20×10^{-10}	6.0×10^{-14}	8.49×10^{-8}	4.24×10^{-11}	2.58×10^{-8}	1.03×10^{-11}
High-pressure spray fire on a Comet machine with a plutonium core	1.0×10^{-6}	0.121	0.0000605	181	0.0907	4.06	0.00162
Earthquake-induced facility failures without fire	0.0001	1.56×10^{-4}	7.8×10^{-8}	0.16	8.02×10^{-5}	0.0638	2.55×10^{-5}

[a] Based on a population of 283,571 persons residing within 80 kilometers (50 miles) of the site.
[b] Increased likelihood of a latent cancer fatality.
[c] Increased number of latent cancer fatalities.

Table C–10 Annual Cancer Risks Due to Accidents under the LANL New Facility Alternative

Accident	Maximally Exposed Offsite Individual [a]	Offsite Population [b, c]	Noninvolved Worker [a]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	1.67×10^{-12}	1.44×10^{-9}	6.12×10^{-10}
Bare, fully reflected or moderated metal criticality	6.0×10^{-18}	4.24×10^{-15}	1.03×10^{-15}
High-pressure spray fire on a Planet machine with a plutonium core	6.05×10^{-11}	9.07×10^{-8}	1.62×10^{-9}
Earthquake-induced facility failures without fire	7.8×10^{-12}	8.02×10^{-9}	2.55×10^{-9}

[a] Increased risk of a latent cancer fatality.
[b] Risk of increased number of latent cancer fatalities.
[c] Based on a population of 283,571 persons residing within 80 kilometers (50 miles) of the site.

Table C–11 Accident Frequency and Consequences under the SNL/NM Alternative

Accident	Frequency (per year)	Maximally Exposed Offsite Individual		Offsite Population [a]		Noninvolved Worker	
		Dose (rem)	Latent Cancer Fatalities [b]	Dose (person-rem)	Latent Cancer Fatalities [c]	Dose (rem)	Latent Cancer Fatalities [b]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	1.0×10^{-6}	0.000872	4.36×10^{-7}	5.25	0.00262	0.572	0.000229
Bare, fully reflected or moderated metal criticality	0.0001	3.20×10^{-11}	1.60×10^{-14}	1.47×10^{-7}	7.37×10^{-11}	9.91×10^{-9}	3.96×10^{-12}
High-pressure spray fire on a Comet machine with a plutonium core	1.0×10^{-6}	0.0331	0.0000166	433	0.216	6.91	0.00276
Earthquake-induced facility failures without fire	0.0001	3.67×10^{-5}	1.83×10^{-8}	0.291	1.45×10^{-4}	0.0257	1.03×10^{-5}

[a] Based on a population of 745,287 persons residing within 80 kilometers (50 miles) of the site.
[b] Increased likelihood of a latent cancer fatality.
[c] Increased number of latent cancer fatalities.

Table C–12 Annual Cancer Risks Due to Accidents under the SNL/NM Alternative

Accident	Maximally Exposed Offsite Individual [a]	Offsite Population [b, c]	Noninvolved Worker [a]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	4.36×10^{-13}	2.62×10^{-9}	2.29×10^{-10}
Bare, fully reflected or moderated metal criticality	1.60×10^{-18}	7.37×10^{-15}	3.96×10^{-16}
High-pressure spray fire on a Comet machine with a plutonium core	1.66×10^{-11}	2.16×10^{-7}	2.76×10^{-9}
Earthquake-induced facility failures without fire	1.83×10^{-12}	1.45×10^{-8}	1.03×10^{-9}

[a] Increased risk of a latent cancer fatality.
[b] Risk of increased number of latent cancer fatalities.
[c] Based on a population of 745,287 persons residing within 80 kilometers (50 miles) of the site.

Table C–13 Accident Frequency and Consequences under the NTS Alternative

Accident	Frequency (per year)	Maximally Exposed Offsite Individual		Offsite Population [a]		Noninvolved Worker	
		Dose (rem)	Latent Cancer Fatalities [b]	Dose (person-rem)	Latent Cancer Fatalities [c]	Dose (rem)	Latent Cancer Fatalities [b]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	1.0×10^{-6}	0.0000626	3.13×10^{-8}	0.016	8.00×10^{-6}	1.52	0.000608
Bare, fully reflected or moderated metal criticality	0.0001	2.18×10^{-12}	1.09×10^{-15}	2.47×10^{-10}	1.23×10^{-13}	2.52×10^{-8}	1.01×10^{-11}
High-pressure spray fire on a Comet machine with a plutonium core	1.0×10^{-6}	0.00497	2.49×10^{-6}	1.55	0.000773	1.00	0.004
Earthquake-induced facility failures without fire	0.0001	2.60×10^{-6}	1.30×10^{-9}	8.88×10^{-4}	4.44×10^{-7}	0.0638	2.55×10^{-5}

[a] Based on a population of 18,074 persons residing within 80 kilometers (50 miles) of the site.
[b] Increased likelihood of a latent cancer fatality.
[c] Increased number of latent cancer fatalities.

Table C–14 Annual Cancer Risks Due to Accidents under the NTS Alternative

Accident	*Maximally Exposed Offsite Individual* [a]	*Offsite Population* [b, c]	*Noninvolved Worker* [a]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	3.13×10^{-14}	8.00×10^{-12}	6.08×10^{-10}
Bare, fully reflected or moderated metal criticality	1.09×10^{-19}	1.23×10^{-17}	1.01×10^{-15}
High-pressure spray fire on a Comet machine with a plutonium core	2.49×10^{-12}	7.73×10^{-10}	4.00×10^{-9}
Earthquake-induced facility failures without fire	1.30×10^{-13}	4.44×10^{-11}	2.55×10^{-9}

[a] Increased risk of a latent cancer fatality.
[b] Risk of increased number of latent cancer fatalities.
[c] Based on a population of 18,074 persons residing within 80 kilometers (50 miles) of the site.

Table C–15 Accident Frequency and Consequences under the ANL/W Alternative

Accident	*Frequency (per year)*	*Maximally Exposed Offsite Individual*		*Offsite Population* [a]		*Noninvolved Worker*	
		Dose (rem)	*Latent Cancer Fatalities* [b]	*Dose (person-rem)*	*Latent Cancer Fatalities* [c]	*Dose (rem)*	*Latent Cancer Fatalities* [b]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	1.0×10^{-6}	0.000213	1.07×10^{-7}	0.162	0.0000811	1.15	0.00046
Bare, fully reflected or moderated metal criticality	0.0001	8.32×10^{-12}	4.20×10^{-15}	3.12×10^{-9}	1.56×10^{-12}	1.99×10^{-8}	7.96×10^{-12}
High-pressure spray fire on a Comet machine with a plutonium core	1.0×10^{-6}	0.0145	7.25×10^{-6}	15.4	0.00772	17.9	0.00716
Earthquake-induced facility failures without fire	0.0001	8.85×10^{-6}	4.42×10^{-9}	0.00902	4.51×10^{-6}	0.0485	1.94×10^{-5}

[a] Based on a population of 239,099 persons residing within 80 kilometers (50 miles) of the site.
[b] Increased likelihood of a latent cancer fatality.
[c] Increased number of latent cancer fatalities.

Table C–16 Annual Cancer Risks Due to Accidents under the ANL/W Alternative

Accident	*Maximally Exposed Offsite Individual* [a]	*Offsite Population* [b, c]	*Noninvolved Worker* [a]
Uncontrolled reactivity insertion in Comet or Planet with a plutonium core	1.07×10^{-13}	8.11×10^{-11}	4.60×10^{-10}
Bare, fully reflected or moderated metal criticality	4.20×10^{-19}	1.56×10^{-16}	7.96×10^{-16}
High-pressure spray fire on a Comet machine with a plutonium core	7.25×10^{-12}	7.72×10^{-9}	7.16×10^{-9}
Earthquake-induced facility failures without fire	4.42×10^{-13}	4.51×10^{-10}	1.94×10^{-9}

[a] Increased risk of a latent cancer fatality.
[b] Risk of increased number of latent cancer fatalities.
[c] Based on a population of 239,099 persons residing within 80 kilometers (50 miles) of the site.

Table C–17 Accident Frequency and Consequences under SHEBA Relocation

Accident	Frequency (per year)	Maximally Exposed Offsite Individual		Offsite Population [a]		Noninvolved Worker	
		Dose (rem)	Latent Cancer Fatalities [b]	Dose (person-rem)	Latent Cancer Fatalities [c]	Dose (rem)	Latent Cancer Fatalities [b]
Uncontrolled reactivity insertion in SHEBA in burst mode	1.0×10^{-6}	18.0	0.009	6,300	3.54	340	0.272
Hydrogen detonation in SHEBA	0.0054	0.0506	0.0000253	18.0	0.009	0.912	0.000365
Earthquake-induced facility failures without fire	0.0001	0.0315	0.0000158	14.3	0.00717	0.565	0.000226
Inadvertent solution criticality in SHEBA	1.0×10^{-6}	0.000139	6.95×10^{-8}	0.052	0.000026	0.00179	7.16×10^{-7}

[a] Based on a population of 450,302 persons residing within 80 kilometers (50 miles) of the site.
[b] Increased likelihood of a latent cancer fatality.
[c] Increased number of latent cancer fatalities.

Table C–18 Annual Cancer Risks Due to Accidents under SHEBA Relocation

Accident	Maximally Exposed Offsite Individual [a]	Offsite Population [b, c]	Noninvolved Worker [a]
Uncontrolled reactivity insertion in SHEBA in burst mode	9.0×10^{-9}	3.45×10^{-6}	2.72×10^{-7}
Hydrogen detonation in SHEBA	1.37×10^{-7}	4.87×10^{-5}	1.97×10^{-6}
Earthquake-induced facility failures without fire	1.58×10^{-9}	7.17×10^{-7}	2.26×10^{-8}
Inadvertent solution criticality in SHEBA	6.95×10^{-14}	2.60×10^{-11}	7.16×10^{-13}

[a] Increased risk of a latent cancer fatality.
[b] Risk of increased number of latent cancer fatalities.
[c] Based on a population of 450,302 persons residing within 80 kilometers (50 miles) of the site.

C.6 ANALYSIS CONSERVATISM AND UNCERTAINTY

The analysis of accidents is based on calculations relevant to hypothetical sequences of events and models of their effects. The models provide estimates of the frequencies, source terms, pathways for dispersion, exposures, and the effects on human health and the environment as realistic as possible within the scope of the analysis. In many cases, the scarcity of experience with the postulated accidents leads to uncertainty in the calculation of the consequences and frequencies. This fact has promoted the use of models or input values that yield conservative estimates of consequences and frequency.

Due to the layers of conservatism built into the accident analysis for the spectrum of postulated accidents, the estimated consequences and risks to the public represent the upper limit for the individual classes of accidents. The uncertainties associated with the accident frequency estimates are enveloped by the analysis conservatism.

Of particular interest are the uncertainties in the estimates of cancer fatalities from exposure to radioactive materials. The numerical values of the health risk estimators used in this EIS were obtained by linear extrapolation from the nominal risk estimate for lifetime total cancer mortality resulting from exposures of 10 rad. Because the health risk estimators are multiplied by conservatively calculated radiological doses to predict fatal cancer risks, the fatal cancer values presented in this EIS are expected to be overestimates.

For the purposes of this EIS, the impacts calculated from the linear model are treated as an upper-bound case, consistent with the widely used methodologies for quantifying radiogenic health impacts. This does not imply that health effects are expected. Moreover, in cases where the upper-bound estimators predict a number of latent cancer fatalities greater than 1, this does not imply that the latent cancer fatality risk can be determined for a specific individual.

C.7 INDUSTRIAL SAFETY

Estimates of potential industrial impacts on workers during construction and operations were evaluated based on DOE and U.S. Bureau of Labor Statistics. Impacts are classified into two groups, total recordable cases and fatalities. A recordable case includes work-related fatality, illness, or injury that resulted in loss of consciousness, restriction of work or motion, transfer to another job, or required medical treatment beyond first aid.

DOE and contractor total recordable cases and fatality incidence rates were obtained from the CAIRS database (DOE 2000a, 2000b). The CAIRS database is used to collect and analyze DOE and DOE contractor reports of injuries, illnesses, and other accidents that occur during DOE operations. The five-year average (1995 through 1999) rates were determined for average construction total recordable cases, average operations total recordable cases, and average operations fatalities. The average construction fatality rate was obtained from the Bureau of Labor Statistics (Toscano and Windau 1998).

Table C–19 presents the average occupational total recordable cases and fatality rates for construction and operations activities.

Table C–19 Average Occupational Total Recordable Cases and Fatality Rates (per worker year)

Labor Category	*Total Recordable Cases*	*Fatalities*
Construction	0.053	0.000139
Operations	0.033	0.000013

Expected annual construction and operations impacts on workers for each alternative are presented in **Table C–20**.

Table C–20 Industrial Safety Impacts from Construction and Operations (per year)

Alternative	*Estimated Number of Construction Workers*	*Estimated Number of Operations Workers*	*Construction Injuries*	*Construction Fatalities*	*Operations Injuries*	*Operations Fatalities*
No Action	0	212	0.0	0.0	7.00	0.003
TA-18 Upgrade	110	212	5.83	0.015	7.00	0.003
LANL New Facility	300	100	15.9	0.042	3.30	0.001
SNL/NM	300	100	15.9	0.042	3.30	0.001
NTS	60	100	3.18	0.008	3.30	0.001
ANL-W	120	100	6.36	0.017	3.30	0.001
Relocation of Security Category III/IV and SHEBA	70	110	3.71	0.010	3.63	0.001

As expected, the incidence of impacts, above and beyond those requiring first aid, do indeed exceed impacts from radiation accidents evaluated in this analysis. However, no fatalities would be expected from either construction or operations of any facility.

C.8 MACCS2 CODE DESCRIPTION

The MACCS2 computer code is used to estimate the radiological doses and health effects that could result from postulated accidental releases of radioactive materials to the atmosphere. The specification of the release characteristics, designated a "source term," can consist of up to four Gaussian plumes that are often referred to simply as "plumes."

The radioactive materials released are modeled as being dispersed in the atmosphere while being transported by the prevailing wind. During transport, whether or not there is precipitation, particulate material can be modeled as being deposited on the ground. If contamination levels exceed a user-specified criterion, mitigative actions can be triggered to limit radiation exposures.

There are two aspects of the code's structure that are basic to understanding its calculations: (1) the calculations are divided into modules and phases, and (2) the region surrounding the facility is divided into a polar-coordinate grid. These concepts are described in the following sections.

MACCS is divided into three primary modules: ATMOS, EARLY, and CHRONC. Three phases are defined as the emergency, intermediate, and long-term phases. The relationship among the codes's three modules and the three phases of exposure are summarized below.

The ATMOS module performs all of the calculations pertaining to atmospheric transport, dispersion, and deposition, as well as the radioactive decay that occurs before release and while the material is in the atmosphere. It uses a Gaussian plume model with Pasquill-Gifford dispersion parameters. The phenomena treated include building wake effects, buoyant plume rise, plume dispersion during transport, wet and dry deposition, and radioactive decay and ingrowth. The results of the calculations are stored for use by EARLY and CHRONC. In addition to the air and ground concentrations, ATMOS stores information on wind direction, arrival and departure times, and plume dimensions.

The EARLY module models the time period immediately following a radioactive release. This period is commonly referred to as the emergency phase. The emergency phase begins at each successive downwind distance point when the first plume of the release arrives. The duration of the emergency phase is specified by the user, and it can range between one and seven days. The exposure pathways considered during this period are direct external exposure to radioactive material in the plume (cloudshine); exposure from inhalation of radionuclides in the cloud (cloud inhalation); exposure to radioactive material deposited on the ground (groundshine); inhalation of resuspended material (resuspension inhalation); and skin dose from material deposited on the skin. Mitigative actions that can be specified for the emergency phase include evacuation, sheltering, and dose-dependent relocation.

The CHRONC module performs all of the calculations pertaining to the intermediate and long-term phases. CHRONC calculates the individual health effects that result from both direct exposure to contaminated ground and from inhalation of resuspended materials, as well as indirect health effects caused by the consumption of contaminated food and water by individuals who could reside both on and off the computational grid.

The intermediate phase begins at each successive downwind distance point upon the conclusion of the emergency phase. The user can configure the calculations with an intermediate phase that has a duration as short as zero or as long as one year. In the zero-duration case, there is essentially no intermediate phase and a long-term phase begins immediately upon conclusion of the emergency phase.

Intermediate models are implemented on the assumption that the radioactive plume has passed and the only exposure sources (groundshine and resuspension inhalation) are from ground-deposited material. It is for this reason that MACCS2 requires the total duration of a radioactive release be limited to no more than four days. Potential doses from food and water during this period are not considered.

The mitigative action model for the intermediate phase is very simple. If the intermediate phase dose criterion is satisfied, the resident population is assumed to be present and subject to radiation exposure from groundshine and resuspension for the entire intermediate phase. If the intermediate phase exposure exceeds the dose criterion, then the population is assumed to be relocated to uncontaminated areas for the entire intermediate phase.

The long-term phase begins at each successive downwind distance point upon the conclusion of the intermediate phase. The exposure pathways considered during this period are groundshine, resuspension inhalation, and food and water ingestion.

The exposure pathways considered are those resulting from ground-deposited material. A number of protective measures, such as decontamination, temporary interdiction, and condemnation, can be modeled in the long-term phase to reduce doses to user-specified levels. The decisions on mitigative action in the long-term phase are based on two sets of independent actions: (1) decisions relating to whether land at a specific location and time is suitable for human habitation (habitability), and (2) decisions relating to whether land at a specific location and time is suitable for agricultural production (farmability).

All of the calculations of MACCS2 are stored on the basis of a polar-coordinate spatial grid with a treatment that differs somewhat between calculations of the emergency phase and calculations of the intermediate and long-term phases. The region potentially affected by a release is represented with a (r, Θ) grid system centered on the location of the release. The radius, r, represents downwind distance. The angle, Θ, is the angular offset from north, going clockwise.

The user specifies the number of radial divisions as well as their endpoint distances. The angular divisions used to define the spatial grid are fixed in the code and correspond to the 16 points of the compass, each being 22.5 degrees wide. The 16 points of the compass are used in the United States to express wind direction. The compass sectors are referred to as the coarse grid.

Since emergency phase calculations use dose-response models for early fatalities and early injuries that can be highly nonlinear, these calculations are performed on a finer grid basis than the calculations of the intermediate and long-term phases. For this reason, the calculations of the emergency phase are performed with the 16 compass sectors divided into three, five, or seven equal, angular subdivisions. The subdivided compass sectors are referred to as the fine grid.

Two types of doses may be calculated by the code, "acute" and "lifetime."

Acute doses are calculated to estimate deterministic health effects that can result from high doses delivered at high dose rates. Such conditions may occur in the immediate vicinity of a nuclear facility following hypothetical severe accidents where confinement and/or containment failure has been assumed to occur. Examples of the health effects based on acute doses are early fatality, prodromal vomiting, and hypothyroidism.

Lifetime doses are the conventional measure of detriment used for radiological protection. These are 50-year dose commitments to either specific tissues (e.g., red marrow and lungs) or a weighted sum of tissue doses defined by the International Commission on Radiological Protection and referred to as "effective dose."

Lifetime doses may be used to calculate the stochastic health effect risk resulting from exposure to radiation. MACCS2 uses the calculated lifetime dose in cancer risk calculations.

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